Journal of Coastal Research	SI	59	98-110	West Palm Beach, Florida	2011

New Ebb-Tidal Delta at an Old Inlet, Shark River Inlet, New Jersey

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ABSTRACT

BECK, T.M. and KRAUS, N.C., 2011. New Ebb-Tidal Delta at an Old Inlet, Shark River Inlet, New Jersey. *In:* Roberts, T.M., Rosati, J.D., and Wang, P. (eds.), *Proceedings, Symposium to Honor Dr. Nicholas C. Kraus,* Journal of Coastal Research, Special Issue, No. 59, pp. 98-110. West Palm Beach (Florida), ISSN 0749-0208.

Shark River Inlet, located on the north New Jersey coast, is served by a federal navigation channel that has until recently required little maintenance dredging. Although possessing a small estuary, the inlet is hydraulically efficient because of the small width to depth ratio of its entrance that is stabilized by parallel jetties. After placement of approximately 4.8 million m^3 of beach nourishment to the north and south of the inlet as part of an erosion-control project conducted in the late 1990s, inlet maintenance increased beyond that anticipated. Analysis of channel and nearshore surveys indicates that an ebb-tidal delta is forming where none had existed previously, attributed to the recent availability of sand from the beach nourishment and a lack of sand prior to that construction. Jetty tip shoals also encroach on the channel, dependent on season, with longshore transport directed primarily to the north during summer (the predominant direction of transport) and to the south during winter. Formation of the ebb delta must be accounted for in the sand budget of the adjacent beaches. After conducting a GIS analysis of ebb delta growth to understand geomorphic trends, the Coastal Modeling System (CMS) was established to numerically simulate waves, current, sand transport, and morphology change. The CMS reproduced observed trends in ebb-delta growth, and multi-year simulations indicate the time scale of approach to dynamic equilibrium of the ebb delta and establishment of natural sand bypassing at the inlet.

ADDITIONAL INDEX WORDS: *Tidal inlet, sediment bypassing, sediment transport, dredging, channel infilling, morphologic modeling, inlet processes.*

INTRODUCTION

The northern Atlantic coast of New Jersey has experienced a severe sediment (sand) deficiency for the past century, resulting in loss of beaches, placement of dense numbers of sand-retention structures such as groins, bulkheads, and seawalls, and overall winnowing of finer sand to leave a coarser lag (Kraus *et al.*, 1988). The beach profile has tended to steepen in approach to equilibrium with the coarser sand. The regional, long-term trend of net longshore sand transport on this coast is directed from south to north (U.S. Army Corps of Engineers [USACE], 1954; Angas, 1960; Caldwell, 1966), feeding the northern Sandy Hook spit and further depleting the sand supply in the nearshore, because little sand can return from the north.

Shark River Inlet is located in Monmouth County along the Atlantic Highlands region of the New Jersey shore and is the northernmost inlet on this coast (Figure 1). The inlet is served by a federally maintained navigation channel connecting the small estuary of Shark River with the Atlantic Ocean. There is no significant river flow to the estuary, which is fed by several small streams. The shallow estuary is situated between upland ridges and has a developed shoreline. Until about the year 2000, the ocean entrance to Shark River Inlet required minor, infrequent maintenance dredging (every 7 to 10 years). Subsequent to year 2000, the surveys by the USACE New York District measured increasing shoaling at the inlet entrance, first from the south and then from the north, necessitating unplanned dredging to maintain the navigation channel. Surveys indicate that prior to nourishment of the adjacent beaches starting in the late 1990s, Shark River Inlet lacked an ebb-tidal delta, noted by Sorensen (1990) in a study of Bradley Beach located north of the inlet. It was anticipated that channel shoaling would increase slightly after nourishment of the adjacent beaches, but re-establishment of an ebb-tidal delta was not considered. Thus, Shark River Inlet has a large and clear signal with which to examine interacting beach and inlet processes and to test numerical simulation models for predicting morphology change at inlets.

This study was performed to understand the causes of recent channel shoaling within Shark River Inlet, the formation of an ebb-tidal delta where one did not previously exist in modern times, and the functionality of the inlet as a sink within a framework of regional sediment management. Channel survey data and bathymetry records were analyzed in a GIS approach,

DOI: 10.2112/SI59-010.1 received 15 December 2009; accepted 14 April 2010.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **New Ebb-Tidal Delta at an Old Inlet, Shark River Inlet, New Jersey**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,Coastal and Hydraulics Laboratory,3909 Halls Ferry Road,Vicksburg,MS,39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

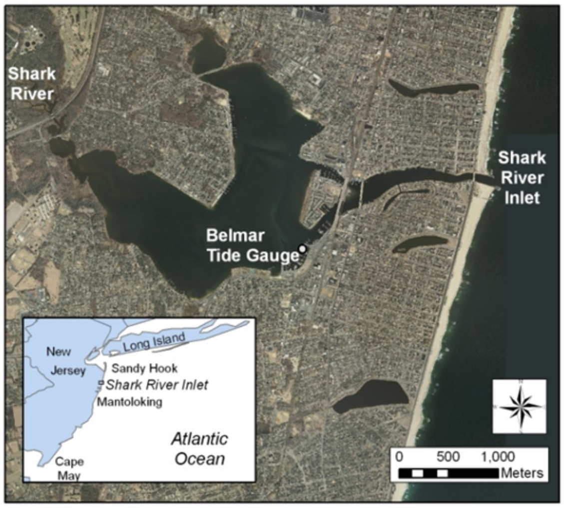

Figure 1. Study area map.

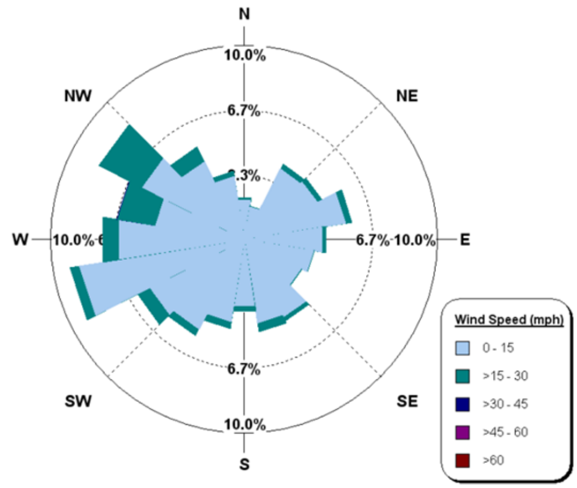

Figure 2. Rose plot of distribution of measured wind speeds from Sandy Hook for the years 1997-99.

and the Coastal Modeling System (CMS) was established at the site to interactively calculate waves, wave-induced current, tidal flow, sand transport, and geomorphology change. Short-term field measurements were also made for verification of the hydrodynamic model.

SITE DESCRITPION

The regional study area for the northern New Jersey coast extends from Sandy Hook, a 10-km long spit located approximately 30 km to the north of Shark River Inlet, to Manasquan Inlet located 10 km to the south (Figure 1). The coastline is oriented north-south with a few small estuaries or lakes located between the Atlantic Highland bluffs. Sediment, primarily consisting of sand along the nearshore and beach face, originates from reworked glacial material and has an average grain size ranging between 0.2 and 0.35 mm. Kraus *et al.* (1988) found that the average nearshore profile for the Shark River area had a median grain size diameter of 0.26 mm. Tide in the area is predominantly semi-diurnal with a spring tidal range of 2 m and neap tidal range of 1 m. Waves arrive out of the north in the winter and from the south in summer, producing a net longshore sediment transport to the north (USACE, 1954; Caldwell, 1966).

Wave Climate

Two distinct meteorological patterns of persistent south-westerly trade winds and the passages of winter storms from the northwest control the wave climate along the New Jersey coast. With the exception of the infrequent arrival of tropical storms, these two patterns produce the bimodal distribution of wave energy. Figure 2 illustrates the frequency occurrence of wind speed and direction at the Sandy Hook National Oceanographic and Atmospheric Administration (NOAA) tide station (No. 8531680) measured for the years 1997-99. As winter storms, or cold fronts, pass from west to east, there is a switch in wind direction from the northwest to the northeast. However, because of the sheltering of the New Jersey Coast located south of Long Island, New York, waves generated from strong northwesterly winds are negligible as the storms pass. It is only after a winter storm has moved east over the open Atlantic Ocean that the area can receive large swell-type waves associated with the frontal passage. Figure 3 illustrates the yearly distribution of wave height and period in separate rose diagrams. For much of the year, southwesterly winds generate fair-weather waves out of the south, whereas frontal passages generate larger swell-type waves that can only approach the northern New Jersey coast from the east.

Jetty and Channel History

Shark River Inlet is stabilized by two parallel rubble stone jetties owned and maintained by the State of New Jersey. Two curved jetties were constructed in 1915, and between 1948 and 1951 the State rebuilt and realigned the jetties to extend straight to the ocean (Angas, 1960). Aerial photographs from 1920 and 1933 illustrate the original curved jetties and the impoundment along the south jetty (Figure 4). Although these jetties have experienced maintenance since 1951, the parallel configuration has continued with the north and south jetties 160 m and 290 m long, respectively, and 91 m apart. A 152 m-long shore-parallel external spur extends northward from the north jetty and was built to protect its landward end during winter storms.

The federal navigation project consists of the entrance channel, which is 5.5 m deep and 45 m wide from the Atlantic Ocean to a point 152 m landward of the inlet, connecting to a channel 3.7 m deep and 30 m wide extending 2 km into the estuary. The navigation vertical datum is mean low water (MLW), tied to a long-term project benchmark on land. In winter 2009, the entrance channel is expected to be widened to .

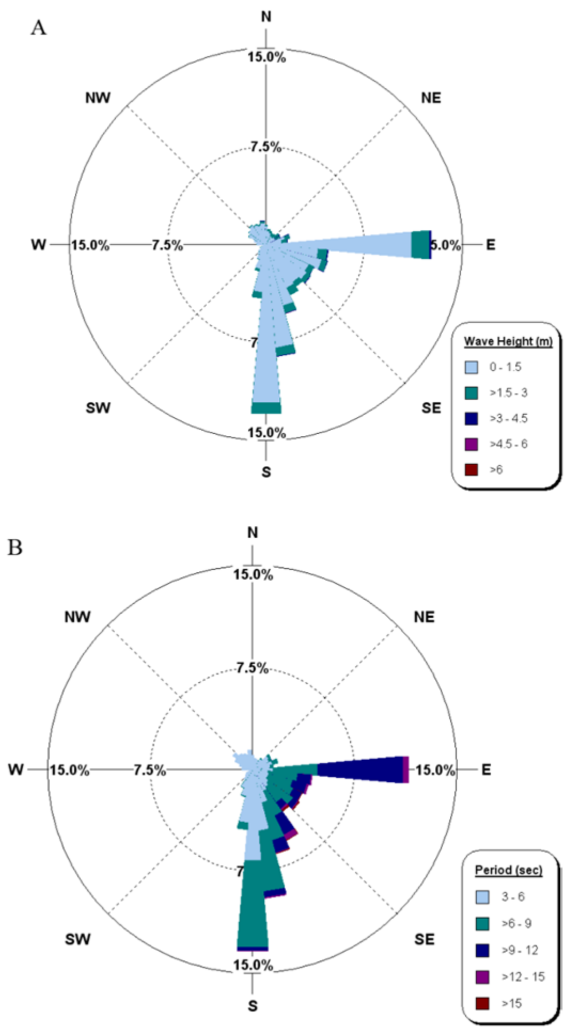

Figure 3. Rose plot of distribution of WIS hindcast (a) wave height, and (b) period for Station 129, Asbury Park, for the 1980-1999 dataset.

Figure 4. A) Shark River Inlet, February-March 1920, post early construction (1915), but during rehabilitation of the original State-built, curved jetties; B) Shark River Inlet, 23 January 1933, post construction of curved jetties and land reclamation of the flood tidal delta and northern portion of the estuary. Note that impoundment along the south jetty, post construction, created a wide beach extending to the jetty tip. Also, following jetty construction was the development of an asymmetric shoal offshore of the inlet, as illustrated by wave breaking in the lower figure.

15 m on each side as an interim measure to mediate the need for excessive dredging.

The inlet, connecting the estuary of Shark River to the ocean, goes from 60-m width at the narrowest section near the Highway 1 Bridge to 200 m at State Road 35. Highway 1 crosses the entrance channel (70 m wide) with two bridge piers located near the center of the inlet. The inlet then divides into two channels landward of the entrance, the north and south feeder channels (40 m and 100 m wide, respectively), which are the original flood channels situated around the now well-developed flood tidal delta known as Shark River Island. Two bridges span this section, Highway 35 and 71, as well as railroad tracks, each with five to ten small piers spanning the channels. Bridge piers will increase flow resistance. Channel cross-sectional area is further decreased due to several shallow and intertidal, oyster-encrusted shoals. Landward of these channels, the estuary opens up to a shallow and relatively small embayment.

Littoral Processes and Sand Budget

Based on a regional sand budget, the long-term net potential longshore sand transport rate has most recently been estimated at around 153,000 m^3/year to the north and the gross transport rate at 696,000 m^3/year (USACE, 2006), in accord with previously reported trends (USACE, 1954; Johnson, 1956; Angas, 1960; Caldwell, 1966). Shark River Inlet is located 17 km north of a nodal zone in longshore sand transport (approximately located near the town of Mantoloking, NJ) that is produced by sheltering of the north New Jersey coast by Long Island, NY, and by the northern continental landmass from waves out of the north (USACE, 1954; Caldwell, 1966). The gross transport rate is the sum of the north- and south-directed rates. The gross transport rate contributes to shoaling of littoral material into the navigation channel as emphasized by Bodge (1993), apart from impoundment and bypassing. Long-term net and gross sand transport rates correspond to potential longshore transport and can be realized only if sand is fully available to be transported in the littoral zone. Littoral material will bypass the channel as well as deposit in it, because shallow channels are not complete traps to littoral transport, especially during storms.

Angas (1960) documents that the south (up-drift) jetty impounded considerable sand volume along the adjacent beach, in contrast to the beach to the north, which was severely eroded. Therefore, in 1958 and 1959, a sand bypassing project was conducted at Shark River Inlet by excavation with a crane and transport by truck. At the time of writing the Angas (1960) paper, a target volume of 172,000 m^3 was expected to be bypassed. More than half of this amount, about 105,000 m^3, had been bypassed in the first winter season. This mechanical bypassing action is in accord with present estimates of both the direction and volume of net longshore sand transport. Angas (1960) also notes that a bar tended to form around the south jetty, directed to the north. The trend for spit elongation from the south is observed in the photographs in Figure 4. However, Angas (1960) states that any material bypassed was believed to arrive to the shore much farther north of the area directly down drift that was deprived of sand, and therefore did not benefit the beach adjacent to the north jetty. Sorensen (1990) concluded that the net and gross longshore transport rates were smaller by an order of magnitude, but we believe the sediment deficiency along this coast at that time was not considered.

As part of the Sea Bright to Manasquan Inlet Beach Erosion Control Project, in 1997 the USACE New York District placed approximately 3.1 million m^3 of fine to medium sand to the south of Shark River Inlet. During 1999-2000, another 2.4 million m^3 of sand was placed to the north of the inlet. The sand was taken from offshore sources. Nine long groins in the Borough of Spring Lake, located south of the inlet, were notched (lowered in elevation) in 1997 and 1998 near the shore to promote sand movement into a local erosion hot spot and straighten the local shoreline (Donohue *et al.*, 2004). In the autumn of 2002, multiple groins were notched, in addition to the nine initial groins, at the same time as the placement of about 172,000 m^3 of sand in Spring Lake (Bocamazo *et al.*, 2003). Construction of the Erosion Control Project and notching of the groins provided sand to partially if not completely reestablish natural longshore sand transport potential in the region of placement. The General Design Memoranda for the Erosion Control Project (USACE, 1995a; 1995b) anticipated increased shoaling and shorter time interval between dredging at the Shark River Inlet entrance to approximately every 2 to 3 years owing to increased availability of sand.

Inlet Processes: Hydraulic Stability of a Small Wave-Dominated Inlet

Shark River Inlet cannot be classified as a river mouth because it does not experience notable freshwater flow that would contribute to maintaining inlet stability. The entrance serves a relatively small estuary complex estimated at 324 ha. Jarrett (1976) found a tidal prism of 4.19 × 10^6 m^3, channel cross-sectional area of 2.79 × 10^3 m^2 and width to depth (hydraulic radius) ratio of 17. The ebb current in this inlet is known to be strong, making navigation and surveying sometimes difficult, but the marinas in the estuary are well protected and experience calm water. The unusually strong current is attributed to hydraulic efficiency imposed by the small entrance width to depth ratio, one of smallest of 108 U.S. inlets and the smallest among 35 Atlantic coast inlets tabulated by Jarrett (1976). A deeper channel exerts less bottom friction on the current.

A harmonic analysis was performed for the month of August 2009 at the nearby ocean tide gauge at Sandy Hook, NJ, operated by NOAA, and a tide gauge at Belmar (Figure 1) maintained in the Shark River Estuary by the U.S. Geological Survey. These data are plotted in Figure 5, and the computed harmonics for the measurements and for the CMS calculations to be discussed below are listed in Table 1. The semi-diurnal components of the analysis show little variation in phase and only a slight reduction in amplitude, indicating little tidal attenuation through the inlet. Smaller, high-frequency harmonics have nearly equal amplitudes and are close in phase. Lack of tidal attenuation and phase difference indicates the efficiency of the narrow inlet channel to flush the small estuary. This hydraulic efficiency owes both to a small width to depth ratio and to negligible impedance from bottom features such as sand waves in the channel entrance.

According to a commonly applied empirical relation (Walton and Adams, 1976), the tidal prism at Shark River Inlet can support an ebb-tidal delta of 0.92×10^6 m^3 at dynamic equilibrium, if sand is available to form this feature. It will be composed of sand that would otherwise reside on the beach and should be accounted for in the sand budget. Inlets on the coasts of northern New Jersey and southern Long Island tend to be wave dominated, as opposed to tide dominated. Hayes (1979) and Davis and Hayes (1984) characterized inlet ebb-delta planform morphology according to tidal range and average incident wave height. Wave-dominated inlets have an ebb delta that is roughly horseshoe shaped around the entrance. Formation of ebb- and flood-tidal deltas is normally calculated as part of the sand budget developed in planning of new inlets to be

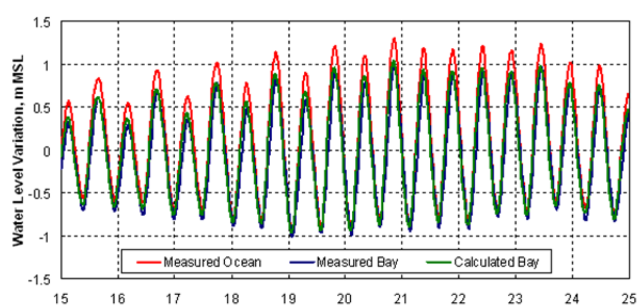

Figure 5. Observed time series of water level at Sandy Hook and Belmar ("Bay") and calculated water level at Belmar.

Table 1. *Tidal Constituents for Sandy Hook, Belmar, and Calculated with the CMS (units of amplitude A in m, and units of phase P in deg)*

	Q1		O1		K1		N2		M2		S2		M4		M6	
Station	A	P	A	P	A	P	A	P	A	P	A	P	A	P	A	P
Sandy Hook	0.014	303.3	0.06	63.78	0.105	120.2	0.17	87.21	0.687	193.5	0.145	283.1	0.022	295.2	0.014	296.9
Belmar	0.014	307.5	0.062	67.58	0.109	126.3	0.15	95.56	0.599	201.2	0.123	297.0	0.021	322.4	0.02	236.2
Calc. Belmar	0.011	310.3	0.054	74.54	0.09	133.6	0.13	109.99	0.561	213.3	0.115	311.2	0.026	3.0	0.016	281.7

opened, and the need for accounting for such a new sand volume at an existing inlet is unusual. Approaching maturity or equilibrium volume, an ebb delta will naturally bypass most of the sand arriving to it unless intercepted by a maintained navigation channel, which would trap some portion. That portion can be bypassed mechanically or hydraulically during channel maintenance.

PROCEDURE

Wave-Driven Potential Sand Transport

In addition to literature cited on sand budget studies, the potential sand transport rate was calculated for assessment prior to intensive numerical modeling with the CMS. The CERC formula (USACE, 2002) was applied to estimate the potential longshore sand transport within the study area. The longshore potential flux P_{ls} was calculated with the wave parameters from the USACE WIS (Wave Information Studies: http://chl.erdc.usace.army.mil/wis) hindcast dataset for Station 129 (located 15 miles offshore of Shark River Inlet) along the Atlantic coast. The transport rate Q is then calculated as:

$$Q = \frac{K}{(\rho_s - \rho)g(1-a)} P_{ls} \tag{1}$$

where K is an empirical coefficient taken here as 0.77, ρ_s is the density of salt water, ρ is the density of fresh water, g is the acceleration due to gravity, a is the porosity (taken to be 0.4), and P_{ls} is the longshore component of wave power at breaking.

Total volume of sand transported was calculated from WIS directional spectra available at hourly intervals from 1980 to 1991. Waves were refracted and shoaled to breaking under assumed plane and parallel contours. The resultant calculations are summarized in Figure 6, a bar graph giving the north- and south-directed, net, and gross transport. The calculations show the dominating influence of the southerly directed waves as compared to waves from winter storms. These calculated annual estimates indicate a net longshore sand transport rate directed to the north except in 1987 and 1992, when there is a small reversal to the south, probably because of the site location near the regional nodal point in longshore transport. The net was almost zero in 1998, an El Niño year. Existence of the nodal point owes to sheltering of winter waves by Long Island, New York, and New England (USACE, 1954; Caldwell, 1966).

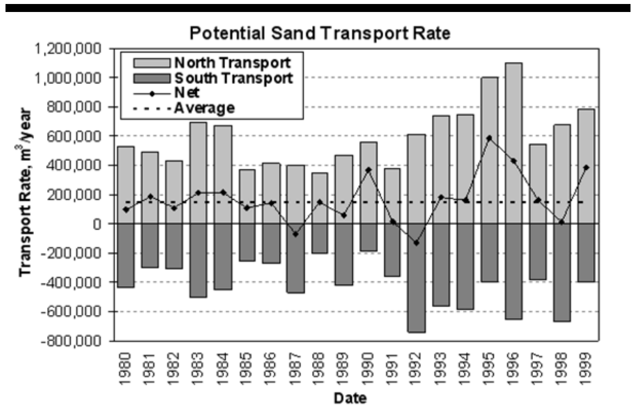

Figure 6. Calculated potential longshore sand transport rates based on WIS station 129 directional spectra.

The calculated net longshore sand transport varies from 100,000 to 200,000 m^3/year, directed to the north, with an average net transport of 170,000 m^3/year. For the 20-year interval, the calculated gross rate averaged 800,000 m^3/year. The direction of net to the north and the values of net and gross rates are in good agreement with trends inferred from a recently compiled long-term sand budget (USACE, 2006).

Short-Term Field Measurements

The current was measured on 20 August 2009 for validation of the CMS. Down-looking acoustic Doppler current profile data (ADCP) were collected for 13 hours on three cross sections

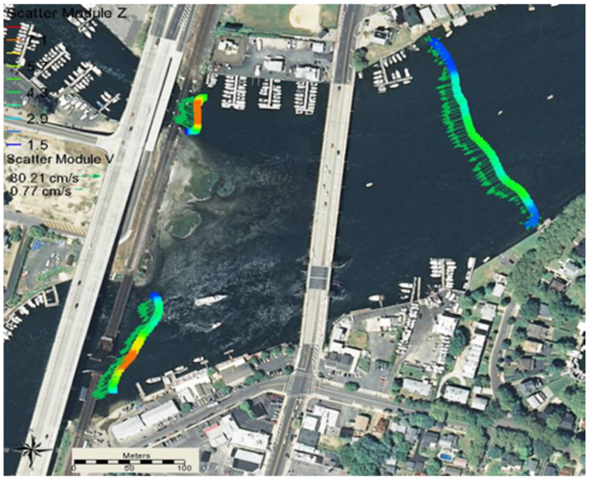

Figure 7. Measured depth-averaged current velocities along surveyed cross sections (CS).

within the inlet (Figure 7). One cross section (CS1) was located in the main channel. The other two cross sections were located on the ocean side of the landward-most bridge (SR-35), covering both the north (CS2) and south channels (CS3). Bay bathymetry was also surveyed with a multi-beam echo sounder. These roving ADCP and bathymetric data were performed with RTK GPS equipment set to a local NOAA tidal benchmark at Belmar.

Dredging Data

The digital dataset provided by the USACE New York District consists of bathymetric surveys of Shark River Inlet from 1995 to May 2009. Their spatial coverage depended on survey purpose and ranged from a minimal survey of the dredged portion of the channel to a larger area covering an extra 200-300 m, laterally alongshore, north and south of the channel. Surveys conducted for dredging may include both a before- and after-dredging survey; and channel-condition surveys are made on an as-need basis. Since realignment of the jetties to their present location in the late 1940s, dredging of Shark River Inlet was relatively infrequent, occurring every 7-10 years. The first set of surveys from 1995, 1998, 1999, and 2000 were channel condition surveys, increasing in frequency following the 1997 beach nourishment. After the condition survey of May 2000, before- and after-dredging surveys increased significantly in regularity to twice a year because the channel began to shoal more frequently. Table 2 lists the surveys conducted by the USACE New York District, analyzed in this study.

Numerical Modeling: The Coastal Modeling System (CMS)

The CMS, a processed-based morphology-change model, was applied in this study. The CMS is a product of the Coastal Inlets Research Program (CIRP) at the US Army Engineer Research and Development Center and is composed of two coupled models, CMS-Flow (Buttolph *et al.*, 2006; Wu *et al.*, 2010) and CMS-Wave (Lin *et al.*, 2008). CMS-Flow is a finite-volume, depth-averaged model that calculates water surface elevation and flow velocity. CMS-Flow is coupled with CMS-Wave that calculates spectral wave propagation including refraction, diffraction, reflection, shoaling, and breaking, and also provides wave information for the sediment transport formulas. CMS-Flow can be driven by an ocean tide, as done here, and by wind forcing. The Non-equilibrium Sediment Transport (NET) model, based on a total load advection-diffusion approach (Sanchez and Wu, 2010), was selected to calculate sand transport rates in CMS-Flow based on the Lund CIRP transport formulae (Camenen and Larson, 2007) from within CMS-Flow for combined waves (breaking and non-breaking) and current. Bed change is then calculated periodically and updated in both the wave and flow models.

The model domain for the CMS covered a local scale of approximately 11 km centrally located around Shark River Inlet. Two separate grids, one for the waves and the other for flow and sand transport, cover the same alongshore distance with the ocean boundary extending seaward 8.5 km for the wave model and 3.5 km for the circulation model. Bathymetry needed to develop the backbay, entrance channel, and ocean depths were assembled from several datasets and converted to mean sea level (which is 0.8 m above MLW from a USACE New York District benchmark) as given by the local tidal datum for Long Branch, NJ (NOAA). Bay bathymetry consisted of data collected during the August 2009 field measurements, and nearshore and ocean bathymetric datasets were a combination of 2005 LIDAR (NOAA) and the National Geodetic Data Center's Coastal Relief Model (NOAA).

CMS-Flow was forced with measured open ocean tide from the Sandy Hook gauge. The calculated water level variation and current velocity were verified through comparison with the bay tide gauge and field measurements for the month of August 2009. Wave data from WIS station 129 provided input parameters for generating spectral waves for driving CMS-Wave. The location of the hindcast station lies along the wave grid boundary at 26 m water depth.

RESULTS AND DISCUSSION

Observed Geomorphology

The bathymetric dataset analyzed, tabulated in Table 2, covers 24 surveys available from January 1995 to May 2009 and describes the geomorphologic change occurring at the inlet. Figures 8 through 11 are examples from the dataset, illustrating depth contour maps set to MLW and with the same horizontal scale. The 1995 and 1998 surveys indicate that the entrance channel was devoid of notable shoals and that the maintained navigation channel extended to deep water without encountering an ebb-tidal delta. All surveys indicate that the beach profile south of the inlet is more advanced seaward as compared to the north side. The south jetty-tip shoal is attributed to the fillet (sand impoundment) on the up-drift side of the inlet, extending the nearshore profile beyond the south jetty, a pervasive feature as apparent in photographs from the 1920s and 1930s (Figure 4).

Table 2. *New York District Survey Data Analyzed in This Study*

Date	Survey Type	Date	Survey Type
1 Jan 1995	Condition	23 May 2006	Condition
6 Jan 1998	Condition	27 Nov 2006	Condition
6 May 1999	Condition	28 Mar 2006	Condition
11 Apr 2000	Condition	30 Aug 2007	Before dredging
16 Apr 2002	Condition	4 Jan 2008	After dredging
6 Dec 2002	Before dredging	25 Mar 2008	Condition
18 Jan 2003	After dredging	9 Jun 2008	After dredging
7 Jul 2003	Condition	31 Oct 2008	After dredging
7 Aug 2003	After dredging	8 Dec 2008	Before dredging
28 Apr 2004	Condition	6 Jan 2009	After dredging
10 Jun 2005	Condition	15 Apr 2009	Before dredging
23 Dec 2005	After dredging	1 May 2009	After dredging

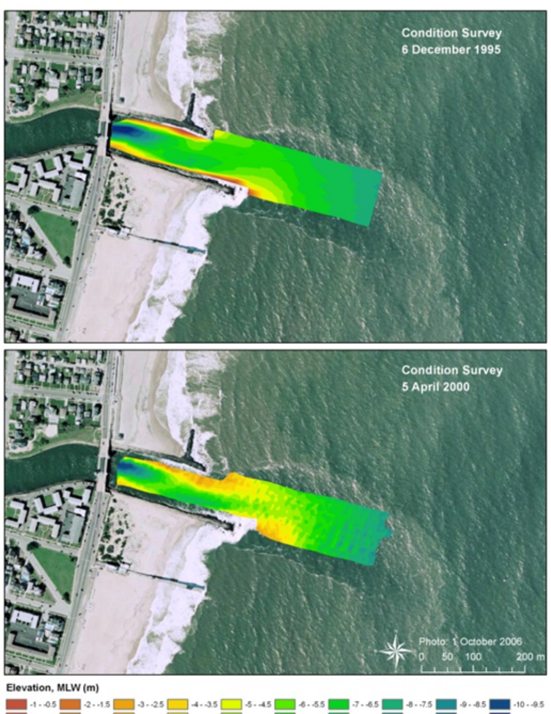

Figure 8. Shark River Inlet entrance, NJ, surveys of December 1995 and April 2000.

The April 2000 survey (Figure 8), made after renourishment of both the south beach (1997) and the north beach (1999-2000), reveal shoals approaching the channel from both north and south, with considerable sand entering the entrance margin on the north. Figure 9 shows before- and after-dredging surveys conducted in December 2002 and January 2003, and indicate the extent to which the channel is now dredged. A substantial influx of sand, from both the north and south, is observed in the December 2002 before-dredging survey and marks the initial formation of a growing ebb-tidal delta. Surveys subsequent to the 2000 survey show a large shoal on either the north or south jetty tip. Such morphologic variation is attributable to seasonal changes in wave direction, when high waves incident from either the north or south and their associated longshore currents would transport sand along these shoals and into the channel, as seen in the July 2003 Condition Survey. Similarly, Williams and Kraus (2010) found seasonal morphologic change at Packery Channel, an inlet in Corpus Christi, TX, where longshore bars approaching the inlet on both sides shift location and volume between seasons.

After the December 2002 dredging, the entrance channel experienced rapid shoal encroachment that required an increased dredging frequency (Table 2). Following the December 2002 dredging, the inlet was surveyed at least twice a year and sometimes more frequently to monitor channel condition. The 7 July 2003 survey indicates formation of an entrance bar, part of the horseshoe-shaped ebb shoal morphology characteristic of wave-dominated inlets (Figure 10). The surveys following in 2004 and 2005 indicate continued impoundment along the north jetty and continued ebb-tidal delta growth. As the sand influx rebuilt both the up-drift (south) and down-drift (north) nearshore profiles alongside the inlet, the horseshoe-shaped morphology becomes more symmetric as seen in the May 2006 survey (Figure 10). The May 2006 survey reveals sand waves over the ebb delta. Such sand waves are formed perpendicular to the

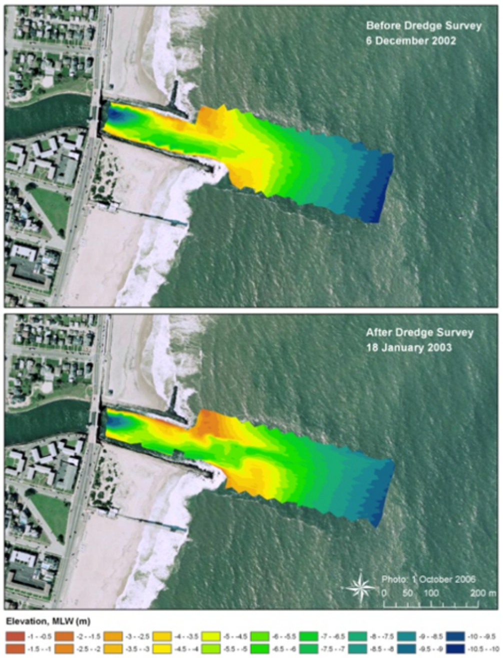

Figure 9. Shark River Inlet entrance, NJ, surveys of December 2002 and January 2003.

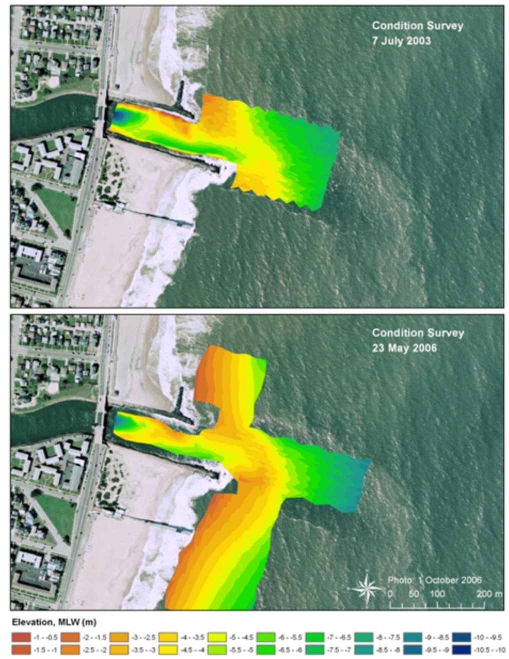

Figure 10. Shark River Inlet entrance, NJ, surveys of July 2003 and May 2006.

dominant current and are indirect evidence of strong longshore strong current transporting sand across the ebb delta and inlet entrance.

Surveys of March and August 2007 (not shown) are consistent with the 2005-2006 survey trends in ebb delta development. Also, a transverse or diagonal bar, a persistent morphologic feature, is observed to have formed across the inlet channel (first seen in the April-May 2002 surveys), running from the tip of the north jetty to the landward end of the south jetty and intersection with the bridge. The transverse bar is in part caused by the tendency of the ebb current exiting from under the north side of the bridge to clear sand in its area of influence, which then deposits where the current velocity decreases. However, the source of sand in the channel is expected to be littoral (marine) in origin and not fluvial or bay derived because of the recent appearance of the bar.

Recent entrance channel surveys had greater coverage, particularly the April 2009 survey (Figure 11), to capture the growth of the ebb-tidal delta. The entrance bar readjusts after each dredging, filling the 5.5 m deep dredged pit to an average of 3 m depth MLW. The shoals along each jetty tip increase in volume seasonally, dependent on the direction of the dominant waves. Asymmetric ebb delta formation, starting about the year 2007, is forcing the channel toward the northeast.

Shoal volume, plotted in Figure 12, increased as compared to the May 1999 survey. The shoal volume was calculated over the area dredged between the jetties, from the Highway 1 bridge seaward to the 5.5 m contour depth. Because of limited coverage of most channel surveys, complete ebb-tidal delta volumes could not be calculated for each survey. However, the total volume increase for the last decade, from May 1999 to April 2009, is calculated to be approximately 90,000 m^3 with 40,000 m^3 within the entrance channel and greater than 50,000 m^3 outside of the jetties.

CMS Simulations

Calculated water level variation and flow are compared with water level from the Belmar gauge and current measured in August, 2009 (Figures 5 and 13). Because the Sandy Hook gauge is located 30 km north of Shark River, the calculations have a slight phase advance in comparison to the bay water level because the tidal wave propagates from north to south on this coast. The ocean gauge typically leads the bay gauge by 20-30 min. Tidal constituents of water level derived from the CMS calculations show good correspondence with the gauge in the estuary at Belmar, including reproduction of the overtides M4 and M6, which originate from non-linearities in tidal wave shoaling in the nearshore and through the inlet.

Current velocity measured on 20 August 2009 is plotted in Figure 13 versus the calculated, centrally-located peak velocity in the three main channels. Comparison of measurements and calculations shows close correspondence (calculations within

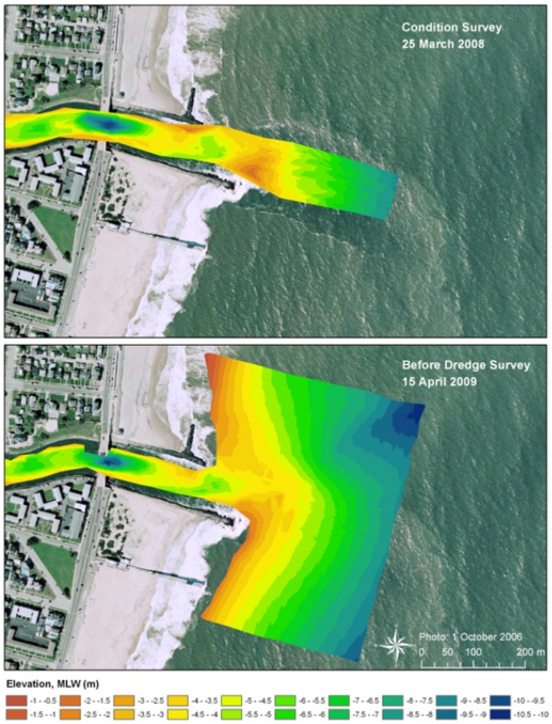

Figure 11. Shark River Inlet entrance, NJ, surveys of March 2008 and April 2009.

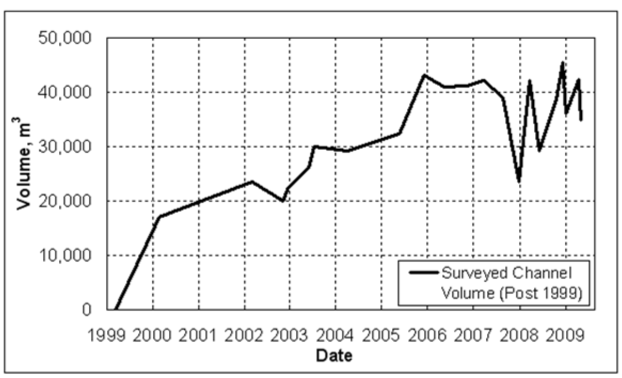

Figure 12. Volumetric change of the entrance channel to Shark River Inlet. Calculations are based on the volume change after 1999 and cover the width of the channel from the bridge out to the -5.5 m (mlw) elevation contour.

5% of measured values) for the main channel (CS 1) and south channel (CS 3), with calculated velocity for the north channel

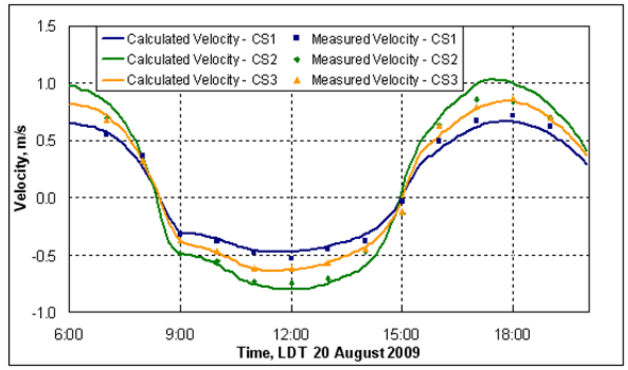

Figure 13. Measured and calculated current velocities at point locations along surveyed cross sections (CS).

(CS2) being higher with a maximum over-prediction of about 10%. The magnitude and general shape of the measured current velocity are well predicted by the CMS, with an average peak velocity of 1.0 m/s in measurements and calculations. The CMS also reproduced a local maximum that occurred at 10 AM.

Three alternative initial conditions were examined with the CMS through calculated morphologic outcomes starting with different initial bathymetries (Figure 14). The ebb-delta growth alternative is defined by an initial bathymetry with a recent shoreline position from 2005, after nourishment of the adjacent beaches, and an inlet bathymetry from 1999. A second initial condition was generated with recent January 2009 bathymetry for a contemporary representation of the inlet after dredging. A third alternative was developed with the recent January 2009 bathymetry, and included a widened dredged channel area extending 15 m on each side.

The growth of the ebb-tidal delta beginning about year 2000 follows the first large-scale injection of sand to the littoral system. Based on the assumption that onset of shoaling was initiated by an increase in sand supply from the adjacent nourished beaches, the CMS was run to predict growth of the ebb delta at the entrance channel as Alternative 1. Sand calculated to be deposited in the channel for a simulation time of 3 years, totaled approximately 30,000 m^3 (Figure 15). This volume is consistent with measured rates of accumulation in the entrance channel, given in Figure 12, where shoaled volume peaked at around 40,000 m^3 after 7 years. The entire calculated ebb-tidal delta after 3 years had a volume of 90,000 m^3. Also, the CMS produced an asymmetric ebb-tidal delta and migration of the entrance channel to the northeast, similar to observations (Figure 11).

The other two alternatives were started from the recent dredged bathymetry of January 2009, with simulations for four months, typical duration of a recent dredging cycle. One of these alternatives started with the existing authorized navigation channel, and the other added a 15-m widener to each side of the channel, a strategy of advance dredging maintenance aimed to prolong navigable depth in the channel. Results from the measured January 2009 and April 2009 bathymetry served to

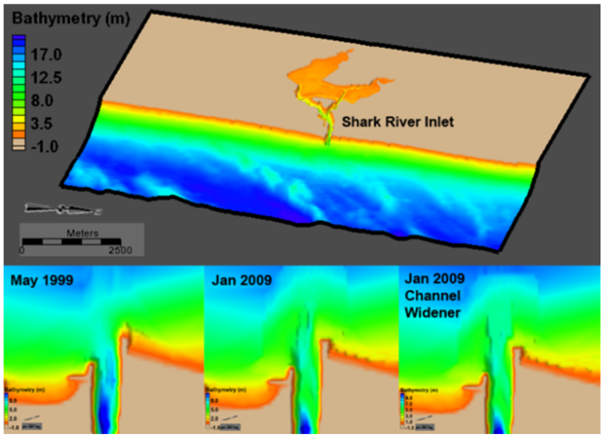

Figure 14. The modeling domain for Shark River Inlet (above) and the three alternatives (below) examined with the CMS.

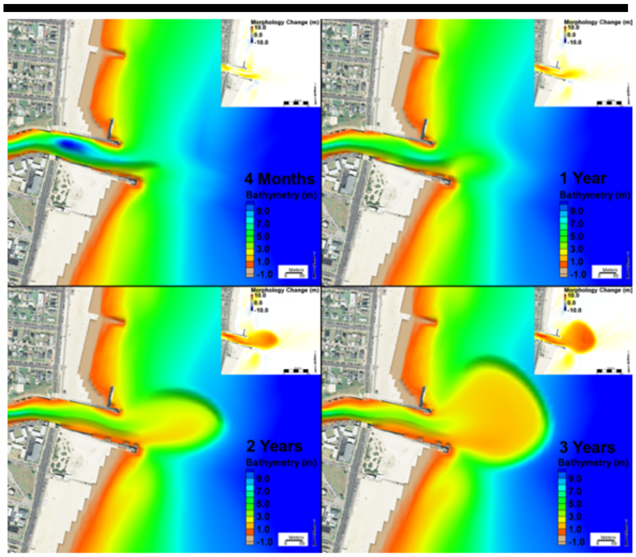

Figure 15. Bathymetry change starting from the 1999 (no ebb-tidal delta) bathymetry.

verify channel infilling rates (Figure 16). Based on the surveys, channel infilling volume expected for the 4-month simulation is about 10,000 m^3 for the entrance channel alone. The measured seaward section of the infilled channel was approximately 1-2 m thick between the limiting depth of 4.2 to 5.0 m over the entrance bar and the dredged depth of 6.3 m (MSL). This thickness represents the initial build up of the entrance bar immediately following dredging, illustrated in April 2009 survey in Figure 10. Calculated limiting depths over the channel were approximately 4.5 m (MSL). The calculated deposition compares well in both volume and morphology, with much of

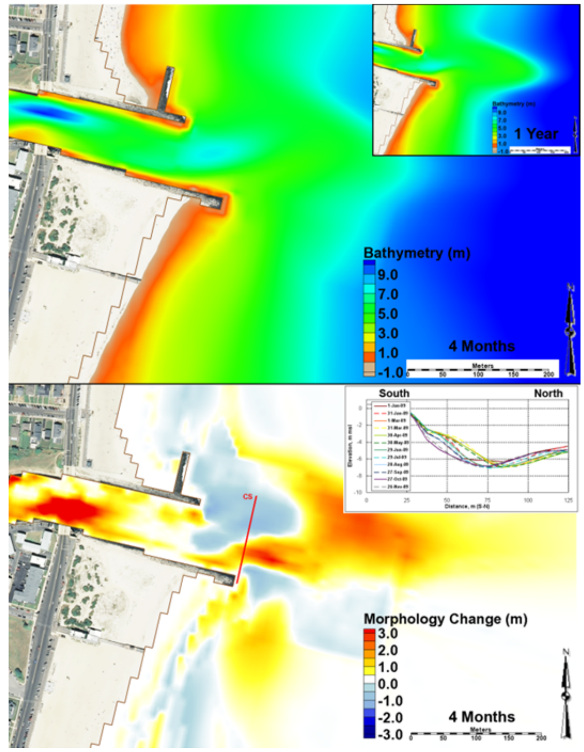

Figure 16. Bathymetry change for present condition (starting from after dredging condition, January 2009).

the deposition occurring along the south side filling in towards the north and development of an entrance bar at the same location relative to the jetty tips.

As a potential short-term strategy to alleviate shoaling, Kraus and Allison (2009) suggested widening the dredged area seaward of the jetty tips. The channel bathymetry from the January 2009 grid was modified to account for a 15 m width increase on both the north and south side. It is expected that the channel wideners will serve as extra accommodation space for sand infilling the dredged channel. Channel infilling volume for the 4-month simulation is greater by 5,000 m^3 (Figure 17) along the updrift southern side of the channel; however, the limiting depth of the entrance bar is 5.5 m as opposed to 4.5 m (MSL) calculated for the existing condition. These preliminary findings therefore justify the increase of dredged area to decrease the dredging interval and indicate that a strategy of optimizing channel widening should be explored. (Later study with the MS done at the time of publication of this paper indicated that 30-m channel wideners will be more efficient.)

NEW EBB TIDAL DELTA SUMMARY

For many decades, the entrance channel to Shark River Inlet remained clear of notable sand infiltration. The morphology of Shark River Inlet, with its narrow entrance channel, small

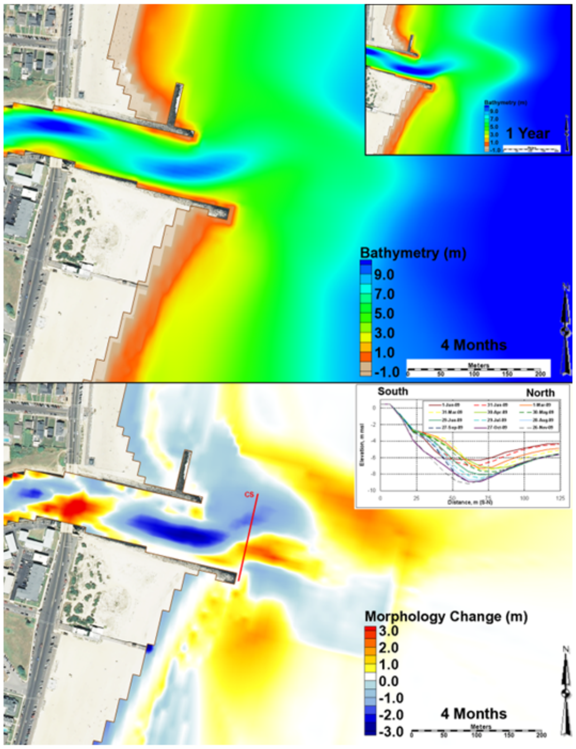

Figure 17. Bathymetry change for present condition (starting from after dredging condition, January 2009) with the 15-m channel widener.

estuary, and until recently narrow adjacent beaches, appears to be unique along the New Jersey and the central Atlantic coast. Persistence of the inlet, despite a relatively small tidal prism (bay surface area) is attributed to its hydraulic efficiency with construction of closely spaced jetties and to a lack of sand to fill the channel. A disruption of that balance occurred with the first regional scale nourishment to this part of the coast.

Substantial nourishment of the adjacent beaches supplied the necessary volume of sand to establish a shallow sand platform as the base for the ebb-tidal delta. The platform formed in the early 2000s and serves as a pathway for sediment to be transported around the jetty tips. As observed in recent surveys (Figure 10), the platform has expanded offshore, allowing development of the new ebb-tidal delta. As the shoaling increases, typically seasonally from the north in winter and from the south in summer, an entrance bar reforms that is characteristic of wave-dominated inlets along this coast. The bar serves as the dominant pathway for sand to bypass the inlet channel. The morphology of the bar, dictated by the direction of current in the form of the ebb jet, will modify the sedimentation patterns.

The Walton and Adams (1976) empirical prediction relation of ebb delta volume based on tidal prism and degree of wave exposure indicate that Shark River Inlet can support an ebb-tidal delta with a volume of 0.92×10^6 m^3. The annual gross transport rate at Shark River Inlet is comparable to the total volume of the ebb-tidal delta and, therefore, the rate of sand bypassing is much greater than the rate of accumulation on the delta. According to the Inlet Reservoir Model (Kraus, 2000), with a constant annual gross transport rate of 700,000 m^3/year, the ebb-tidal delta will reach 90% of equilibrium volume in about 3 years. In contrast, the total volume presently accumulated in the ebb delta since 1999 is only about 90,000 m^3. Smaller-than-expected ebb-delta volume suggests that the delta is competing with the existing steep beach profile for sand volume over the region, warranting further investigation and requiring additional survey area coverage.

Volume in the entrance channel increased rapidly from the year 1999 to about 2005, thereafter approaching approximately 40,000 m^3 (Figure 11). Frequent dredging necessary after 2006 has limited further growth. Approach to equilibrium channel volume indicates that a greater amount of sand will be bypassed. The channel area (18,000 m^2) tends towards a depth of 2.0 m (MLW) under shoaling, so that dredging to a maintained navigation depth of 5.5 m accounts for this volume. Here, volumes persistently reach a 20,000-30,000 m^3 limit in the shoaling portion of the channel. Volume calculations do not include areas adjacent to the channel, because of lack of survey coverage.

CONCLUSIONS

The Shark River Inlet navigation channel functioned well for decades with only minor sand shoaling in the entrance, so it was not a sink for beach sand. Natural sand bypassing must have occurred, but the limited supply did not allow formation of an ebb-tidal delta. The fillet on the south side has always been located close to the south jetty tip and allowed bypassing of sand across the entrance to the northern beaches. Following the first nourishment on the south side in 1997, sand could begin to build a platform for the entrance bar to develop off the tip of the longer jetty. It was not until 2000 that the northern nourishment was completed, after which notable channel shoaling began. In the context of the new morphodynamics at Shark River Inlet, planning with respect to long-term operation of the inlet must be carried out with concern for regional management. In particular, about 1 million m^3, about one-fifth of the volume of material placed on the beach for the erosion-control project, is expected contribute to forming the ebb-tidal delta and must be accounted for in the sand budget.

The CMS, driven by tide and hindcast waves, was capable of reproducing observed trends in ebb-tidal delta development and changes in volume of notable morphologic features. The modeling system was verified by reproducing observed water levels in the Shark River estuary and current velocity in the inlet. The CMS was then applied as an example of evaluating selected alternatives for reducing dredging frequency in maintaining the inlet navigation channel.

ACKNOWLEDGMENTS

This study was jointly funded by the U.S. Army Engineer District, New York, and the Coastal Inlet Research Program (CIRP) at the U.S Army Engineer Research and Development Center. Discussions with and information provided by New York District staff Lynn M. Bocamazo, Adam B. Devenyi, Jessica Fischer, Gerlyn T. Perlas, John F. Tavolaro, and Edward Wrocenski are greatly appreciated. Permission was granted by Headquarters, U.S. Army Corps of Engineers, to publish this information.

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